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REPORT ON

THE FOURTH INTERNATIONAL SYMPOSIUM ON

RAREFIED GAS DYNAMICS

Toronto, July 14-17, 1964

Sponsored by

Air Force Office of Scientific Research, National Aeronautics and Space Administration and Office of Naval Research under Grant No. Nonr (G)-00068-64. Program arrangements by UTIAS

by

G. N. Patterson, Chairman

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ABSTRACT

The Fourth International Symposium on Rarefied Gas Dynamics was held in Toronto on July 14-17, 1964. This meeting was sponsored by the Air Force Office of Scientific Research, the National Aeronautics and Space Administration and the Office of Naval Research under Grant No. Nonr (G)-00068-64. The program was arranged under the chairmanship of Dr. G. N. Patterson by the staff and students of the Institute for Aerospace Studies. This report contains reviews prepared during the meeting of papers in the following areas: transition flow, experimental techniques and apparatus, surface interactions, kinetic theory, molecular beams, internal flow, and rarefied plasmas and shock structure. Appendices are added giving the technical program, a list of delegates and information on the First International Aerospace Exhibition in Canada held as part of the general program.

TABLE OF CONTENTS

1. INTRODUCTION

The Fourth International Symposium on Rarefied Gas Dynamics was held in Toronto, Ontario, Canada during the four days July 14-17, 1964. The meeting was organized by the staff of the Institute for Aerospace Studies. Sponsorship was provided by the Air Force Office of Scientific Research, the National Aeronautics and Space Administration and the Office of Naval Research under Grant No. Nonr (G)-00068-64. Details of the program of papers were the responsibility of Dr. J.H. de Leeuw, who is also the editor of the Proceedings.

This report contains surveys of the various sessions made by members of the staff of the Institute for Aerospace Studies prepared at the time of the meeting. The meeting was arranged by the papers committee in the following ten groups and a panel discussion: (1) Transition Flow - Experimental I, (2) Transition Flow - Theoretical I, (3) Experimental Techniques and Apparatus, (4) Transition Flow - Theoretical and Experimental II, (5) Surface Interactions - I, (6) Kinetic Theory, (7) Molecular Beams, (8) Internal Flow and Rarefied Plasmas, (9) Surface Interactions - II, Miscellaneous Papers, (10) Shock Structure, (11) Discussion and Assessment of the Highlights of the Fourth Symposium.

The following were appointed to the Advisory Committee:

Edmond A. Brun	H.W. Liepmann
Raymond L. Chuan	W. Petrie
F.M. Devienne	W.J. Price
Immanuel Estermann	Ronald F. Probstein
Harold Grad	S.A. Schaaf
D.W. Holder	L.I. Sedov
W.P. Jones	R.E. Street
H.H. Kurzweg	F.R. Thurston

A Steering Committee on Future Plans met on July 14, 1964 to discuss the desireability of a Fifth Symposium, the location of this meeting and its chairman. Those attending this meeting were: E.A. Brun, R.L. Chuan, R.D. Cooper, J.B. Fenn, H. Grad, D.W. Holder, H.H. Kurzweg, J. Laufer, H. Oguchi, G.N. Patterson, W. Petrie, W.J. Price, E.W.E. Rogers, M. Rogers, F. Schultz-Grunow, L.I. Sedov, F.S. Sherman, J. Souquet, R.E. Street, and F.R. Thurston. It was unanimously agreed that a Fifth International Symposium on Rarefied Gas Dynamics should be held at Oxford University in 1966, under the chairmanship of Professor D.W. Holder.

A program of suitable entertainment was organized beginning with a reception by Dr. C.T. Bissell, President of the University of Toronto. A special effort was made to welcome and look after the wives of delegates since it is a matter of experience that delegates can settle more effectively into a technical atmosphere when they know the distaff side of the family is enjoying the visit also.

The chairman wishes to thank a number of people who provided key assistance. The highly competent assistance of Dr. J. H. de Leeuw in arranging the technical sessions and the successful organization by Dr. I. I. Glass of the first International Aerospace Exhibition to be held in Canada were particularly appreciated. My special thanks go also to Mr. S. J. Townsend for his careful supervision of the publication of the program; Mr. W. H. Kubbinga, Mr. S. R. M. Sinclair, Mr. J. H. McCormack for excellent lecture room facilities and to Mrs. S. E. Wyse, Mrs. J. V. Dublack, Mr. E. A. McMillan, Miss J. A. King and Mrs. P. L. McCormack for their unfailing clerical and other assistance.

The Proceedings of the Fourth International Symposium on Rarefied Gas Dynamics has been edited by Dr. J. H. de Leeuw and will be published by Academic Press. A Book of Abstracts was prepared for use at the meeting.

1. TRANSITION FLOW - EXPERIMENTAL - I (N. M. Reddy)

Seven papers were given in this Session. These seven papers can be classified into three catagories, namely;

1. Pressure, heat transfer and skin friction measurements along flat plates and wedges in the transition regime (extended up to free molecule limit).

2. Drag measurements in the transition regime.

3. Miscellaneous.

The above three catagories of work are summarized below.

1. Heat transfer and skin friction data were presented in two papers given by A. Burke and R.J. Vidal of Cornell Aeronautical Laboratory. The other paper was given by I.E. Vas of Princeton University. The data presented in the two papers from C.A.L. was mainly in the transition regime. They were able to fill up the gap between continuum limit and free molecule limit very nicely. The surface slip and temperature jump effects are discussed. All the experimental results are very well correlated with existing theories and discrepancies are noted. It is worthwhile to note the remark from Burke's paper, that the usual hypersonic viscous-inviscid interaction as predicted by the theories of Cheng and Bertram is not observed in this regime. In these experiments a new gauge (pressure transducer type) has been used to measure skin friction which is simpler compared to the classical skin friction meter. I.E. Vas presented pressure data measured on flat plates and cones obtained in low density wind tunnel. A few remarks about the wind tunnel facility are worth mentioning. The wind tunnel is quasi continuous hypersonic tunnel with testing times in the order of 25 minutes as compared to the shock tunnels with a few milliseconds testing time. Thus in this type of tunnel hot wall conditions can easily be obtained which is impossible in a shock tunnel. In this respect the hot wall data is unique.

2. Drag measurements in Transition Regime.

There were two papers in drag measurements , one is from the University of California, Berkeley, and the other from Paris University. Berkeley people have obtained new data of cylinder and strip drag in near free molecule regime at high Mach numbers using free jet testing. By defining the mean free path using viscosity relation, they were able to correlate the cylinder drag data better with theory. Also using modified Krook's model, they presented theoretical results for cylinder equilibrium temperature and sphere drag, which agrees fairly well with experimental results. From these results it may be concluded that the modified Krook's model represents nearly the actual conditions. E.A. Brun from Paris University presented drag data for cylinders and strips in transition regime, at subsonic and supersonic speeds for various speed ratios. He also presented drag data for a number of cylinders and blades kept side by side to study the interaction phenomenon. Some important conclusions can be drawn from these results about optimum spacing and speed effects on total drag. Successful application of Krook's model to estimate drag in near free molecule flow regime is demonstrated from these types of experiments.

3. The last two papers can be classified under miscellaneous group.

I. Wada presented a paper about the application of electron-densitometer to measure density profiles over flat plate in hypersonic stream. Pressure profiles were derived from density profiles by assuming surface temperature constant. By comparing the pressure data with already existing theory and experimental data, the successful application of electron densitometer in low density hypersonic flows is demonstrated. Even though the data obtained is not new, using this method, the time dependence of density at any geometrical location can be obtained, which is very useful to study the unsteady flow phenomenon. Some preliminary pressure measurements over steps and cones at supersonic speeds obtained in the low density wind tunnel at the NPL were presented by E.W.E. Rogers.

Throughout this session, there were only questions about clarification of some experimental details like correction for transpiration effects in pressure data, installation of skin friction meter, etc.

SUMMARY OF THE WHOLE SESSION

This session can be best summarized by referring to the "Discussion and Assessment of the High Lights of the Symposium" that followed immediately after the Symposium under the chairmanship of Prof. D.W. Holder. F. S. Sherman spoke about this session. He commended the work done at CAL. He remarked about the advantage of using free-jet testing over shock tunnels where one encounters thick wall boundary layers. Also he noted that the present state of calibration of test section flow is not sufficient to predict the complete flow phenomenon over bodies. Viscosity of the free stream flow cannot be estimated accurately due to lack of collision cross-section data. Somebody in the audience suggested using space chambers to build large low density wind tunnels in Universities.

2. TRANSITION FLOW - THEORETICAL - I (S. R. M. Sinclair)

2.1 A Uniformly Valid Asymptotic Theory of Linearized Rarefied Gas Flows Under Nearly Free Molecular Conditions: Y. P. Pao

Pao proposes a uniformly valid asymptotic theory for the simple nearly free molecular flow problem of a two dimensional cylinder rotating in an infinite gas otherwise at rest. The BGK model equation is used.

The description of a flow field by the free molecular solution is only valid in the inner region - a region within a distance much larger than the body dimension but much smaller than the mean free path. Outside this region, the collisional effects cannot be neglected even in the lowest order approximation and hence Pao states that a systematic method of obtaining higher order collisional corrections cannot be achieved based on free molecular solution only. The solution of Pao is carried out in the inner and outer regions with different independent variables in each. The two soltuions automatically match in the intermediate region giving a uniformly valid solution.

2.2 Drag on a Cylinder in Nearly-Free Molecular Flow: Marion H. Rose

Dr. Rose presents a method of computing the drag on a cylinder traversing a neutral rarefied gas in the hypersonic range. The method accounts for all collisions and not merely "first collisions" and is in this sense an exact first order calculation. The distribution function is determined at a point D many object diameters away from the body surface but well within a mean free path. The Krook equation with an additional point source term to represent the body is used rather than the complete Boltzmann. The source function is represented analytically by a Dirac delta term.

The results of this solution can be improved by an iterative procedure proposed by Grad in which each consecutive solution is used to improve the source term for the next iteration.

The distribution function calculated at D is extrapolated close to the body in order to calculate the drag. Since collisions are rare in this region, this seems justified.

In the discussion period Talbot questioned the use of the δ-function in hypersonic flow since it implies symmetry. It was made clear that only the front side of the body was considered in the solution.

2.3 Bimodal Two-Stream Distribution and Compressible Couette Flow: J. W. Beck

Beck gives a solution for the compressible Couette flow problem based on the line of sight principle proposed by Lees (1959). Instead of choosing a local Maxwellian for each of the two streams, as Lees did, Beck chooses a weighted sum of two Maxwellians for each stream in his bi-modal two-stream distribution. In the general case, twelve unknown space-dependent functions, including the four weight or influence functions must be found by the usual moment method.

The advantage of this method lies in the greater generality of the distribution function and in the better representation of the physical behavior in the high Knudsen number range. The double maximum in the distribution function for the non-linear case can be reproduced. The method is valid for the entire range of Knudsen numbers.

The results of this method are in reasonable agreement with the non-linear results of Lees and Liu (1959) and the experimental results of Kuhlthau (1953).

In the discussion period, Ziering questioned the use of full range Gaussians to approximate conditions near the boundary. The point was not completely resolved. However, looking at the graphs of Beck's influence functions, it is evident that at the walls his distribution functions reduce to half Gaussian. The full-range nature appears gradually and continuously with increasing distance from the wall.

2.4 Improved "First-Collision" Model Theory: M. Lunc

Lunc gave a philosophical discussion of his improved "First-Collision" model kinetic theory. The model results are consistent in the Knudsen number range from 1 to ∞ and Mach number range from 4 to ∞ with results published recently by Maslach and Schaaf concerning drag on cylindrical bodies in rarefied gas flows.

The method consists of dividing the flow into three distinct gases the gas coming from infinity directly without collisions with reflected molecules, the reflected molecules before collision with the stream from infinity and a single Maxwellian component composed fo molecules of the previous two after mutual collisions. The drag on a body in such a flow is calculated by summing the contributions from the three components. The problem is to find the physical characteristics and impact frequencies of the last two components.

When questioned by Willis, Lunc stated that the difference between his present calculations and his previous cold wall solution is quite large at lower Knudsen numbers.

2.5 Steady Expansion at High Speed Ratio Using the B-G-K Kinetic Model: J.W. Brook and R.A. Oman

Brook and Oman present a numerical solution for axially-symmetric and two dimensional steady free expansions of a monatomic gas. The B-G-K model of the Boltzmann equation is used.

The results displayed for the streamwise temperature variation show a break away and asymptotic leveling out from the equilibrium valve. An interesting feature of the calculation is that this breakaway point and freezing temperature for the jet depend markedly upon the speed ratio at the initial point chosen to start the computation as well as the sonic Reynolds number. The authors attribute this dependence to the importance of the exact form of the initial distribution function. Since they choose a Maxwellian at the initial point they are, in fact, forcing the flow to be Maxwellian in a region of finite gradients.

Oman indicated that further studies are being considered using better approximations to the initial distribution function and possibly molecular models which include internal degrees of freedom and their different relaxationtimes.

2.6 A Discrete Ordinate Technique for the Linearized Boltzmann Equation with Application to Couette Flow: B. Hamel and M. Wachman

A discrete ordinate solution for the linearized Boltzmann equation is formulated. In contrast to the methods of previous investigators which have postulated models to replace the Boltzmann collision term or utilized moment methods, this completely numerical method is approximate only in its use of numerical truncations.

Two distinct quadrature formulas - the Gauss-Hermite full-range and the Gauss-Laguerre half-range formulas are used. Mixing ratios of these two quadratures in a particular flow region depend upon the full-range or half-range nature of the distribution function expected. In this way the effects on the distribution function of boundaries and intermolecular collisions can be accounted for.

The method is applied to the case of linearized Couette flow for hard sphere molecules and the results are in good quantitiative agreement with previous work (Gross and Ziering, 1958; Cercignani, 1963).

It is pointed out that this method is analogous to a method proposed by Krook for non-linear problems. Krook suggested the use of various combinations of full-range and half-range polynomial expansions for different Knudsen number regimes.

Ziering suggested the use of Maxwell molecules to avoid the inherent singularity in the hard sphere representation.

3. EXPERIMENTAL TECHNIQUES AND APPARATUS (J.C. Lafrance and K. Graf)

The first paper, by Ashkenas and Sherman, reviewed the characteristics of free jets. Many of the essential features of free jets were presented. The most important scaled parameters considered were axial Mach number, impact pressure, radial density, and location and diameter of the Mach disc. As well, some characteristics dependent on pumping speed were discussed. The theoretical relations showed excellent agreement with experimental data obtained by the authors. Clearly, these parameters are of extreme importance in the design of new facilities as well as in the "free-jet" operation of existing facilities.

It was shown that free jet expansions in non-continuum flows gave superior testing flexibility (larger isentropic core, larger Mach number range, etc): than nozzle expansions except in the case where the nozzle walls are cryogenically cooled.

The paper by E.P. Muntz showed a Doppler shift method for determing the actual gas velocity distribution function, along one coordinate axis at a time. For most laboratory plasmas, the gas temperature is low, so the Doppler shift due to gas particle velocity is small, and is usually obscured by the presence of hyperfine structure, Stark, collision, and natural broadening. The 5015.67 Å line in Helium was found to be suitable for analysis, and consequently Helium was used as the test gas.

For these measurements, the resolution of the viewing spectrograph is of prime importance. The observed response requires interpretation (or correction) to account for the resolving characteristic of the instrument used. A Fabry-Perot etalon, calibrated with a laser, was employed to measure half-widths that were typically 0.03 Å. The experimental results obtained were in good agreement with the known temperature of the gas.

The third paper by K.W. Rogers et al and the fourth paper by V. L. Potter et al dealt with relating pressure measurements in a cavity to ambient pressure measurements in a region connected to the cavity by an orifice. Different geometrical configurations were considered and compared with the Chambre-Schaaf and momentum-flux theory. An attempt was made to scale orifice size effects in terms of Knudsen numbers.

The fifth paper by D.S. Rigney et al dealt with a discharge probe using the principle of the Paschen curve to obtain gas density measurement in the 10^{-7} to 10^{-5} gm/cm^3 region. It was shown that reliable measurements would be obtained if the current through the discharge is controlled by an electronic circuit to prevent deterioration of the electrodes. It was also shown that by measuring the increased density in a ducted section of a probe and comparing this measurement to a discharge in an ambient portion of the flow, the Mach number of the flow could be deduced.

In the sixth paper, by E. Mayer et al, a theoretical picture of the behaviour of Mach 3 flow impinging on a cryocooled (liquid Helium) flat plate normal to the flow was put forward, and checked with experiment. The experimental results showed that 80% of the incident flow is condensed during the shock free operation of the freeze-out surface. The pumping action was effective and no shock wave formed on the cold surface for a sticking probability as low as about 0.45, which occurred at a temperature of 30^{o}K. Above 30^{o}K, a low shock formed.

The seventh paper, by W.N. McDermott et al, demonstrates the great advantage of cryopumping the boundary layer in low density wind tunnel nozzles. The wall cryopumping remained effective to a supply gas temperature of at least 1500^{o}K and produced a 5 to 10-fold increase in isentropic core diameter.

The final paper by Iacobellis and Knuth presented design and operating data for a radial flow turbomolecular pump. The theoretical considerations take into account the blade thickness. The radial flow pump has larger flow rate than axial models and therefore avoids one of the main limitations of axial pumps. In agreement with their prediction, the pressure ratio and speed factor are found to vary nearly exponentially with rotor speed and is relatively insensitive to variation of gas loads. The pressure ratio across the pump was 6 to 8 at 3400 rpm. The pump was designed for speeds up to 5000 rpm but rotor vibration problems have limited operations to 3400 rpm.

4. TRANSITION FLOW II, THEORETICAL AND EXPERIMENTAL (Y.Y. Chan)

Flow over a flat plate provides an excellent model for studying the dynamics of gases. It is simple in geometry. It provides the complete spectrum of flow regimes from free molecular flow near the leading edge to continuum flow far downstream of the leading edge, and in between, the transition regime. In this session, three papers are devoted to this problem.

Presentation of papers is summarized as follows:

4.1 Kinetic Theory of the Leading Edge: S. Ziering, L. Chi and R. Fante

The leading edge problem was considered by the Bhatnagar, Gross and Krook model of the simplified Boltzmann equation. In order to describe the near free molecule domain accurately, the distribution function was separated into various domains. The collisionless solution at the lead-

ing edge could then be obtained. When the collisions were retained, the equation was then a non-linear partial differential equation which could be solved by numerical method. An approximation scheme was considered by linearization of the equation using the small disturbance technique.

The question of how accurately the B-G-K model would represent the actual flow was asked during the discussion period. The tests of it would rely on its more complete solution and comparison with experimental results.

4.2 The Incipient Continuum Flow Regime Near the Leading Edge of a Flat Plate in Hypersonic Flow: J.M. Ii and R.E. Street

The transition regime was considered by approaching from the continuum side. The Navier-Stokes equations were solved by a series expansion technique based on a parameter which was proportional to the inverse square root of the Reynolds number based on the mean free path of the molecules in the free stream. A shock wave which was assumed to be thin provided the upper bound of the flow and a slip condition was used on the surface of the plate.

In this region, however, it was in doubt that the shock wave could still be thin. The diffusive effect of the shock should be considered within this range.

4.3 Investigations of the Flow Near the Leading Edge of a Heating Flat Plate in a Mach 0.5 Air Flow: S. A. Gordon

Experimental results were presented for a series of measurements conducted in the UTIAS Low Density Wind Tunnel to determine the nature of the flow field in the neighbourhood of the leading edge of a heated flat plate in a subsonic air stream. Molecular speed ratio and total temperature distributions above the plate were shown. It was shown that the leading edge disturbance reached up to ten mean free paths ahead of the body. This upstream influence of the leading edge was not predicted by theory. The data were then used to determine an accommodation coefficient close to the leading edge and farther downstream.

It was interesting to note that some results obtained by numerical solutions of the kinetic equation presented on the following day did show good agreement with these experimental results.

4.4 The Aerodynamic Drag Torque on a Rotating Sphere in the Transition Regime: R.G. Lord and P.J. Harbour

An experimental and theoretical study has been made of the problem of an isolated sphere rotating in a stationary gas. The aerodynamic drag torque experienced by a magnetically suspended test sphere was measured over a wide range of Knudsen numbers from continuum to free molecular flow in air and krypton. A method of correlating the data under a single parameter was also developed.

In the discussion period it was pointed out that this correlation was there only when both the flow Mach number and the viscous dissipation were small.

4.5 Some Experiments on the Flow of a Rarefied Gas Through a Circular Orifice: A. K. Sreekanth

The free jet technique has been used recently in experimental work to produce high speed low density flows for tests of models. Information about the jet produced by a simple circular orifice and the mass flow through the orifice would be required for design of a free jet testing system. In this work, the flow field of a jet through a circular orifice was investigated at very low and moderate pressure ratios. The mass flow for different pressure ratios at a fixed Knudsen number was also recorded. It was shown that the pressure distribution across the jet exit agreed well with the Maxwellian equilibrium distribution for low Knudsen number flow. However, for high Knudsen number flow, the flow deviated markedly from a Maxwellian distribution.

5. KINETIC THEORY (S.J. Townsend)

5.1 Steady-State Oscillations in a Gas: Weitzner

The steady state oscillations in a gas of semi-infinite extent which are generated by a harmonically oscillating boundary are examined. The linearized one-dimensional Boltzmann equation using the Krook model is solved by a spatial Laplace transform. One advantage of this approach to the propagation of sound over the study of the dispersion relation obtained by truncating a set of moment equations, and using eigentheory for the collision integral, is that the continuous spectrum eliminated by the truncation procedure can be studied.

The presence of an observable sound wave depends upon the observation being taken many mean free paths from the wall. The wave train is observable over only a limited length and the number of wavelengths seen is of the order of the collision frequency over the oscillation frequency. If this ratio is not large enough, no coherent oscillation is observable anywhere. Experimental values of this ratio are almost within the range of verifying the theory.

5.2 Sound Propagation in Rigid Sphere and Maxwell Force Law Gases: Sirovich and Thurber

The early kinetic theory of sound propagation, based on the Boltzmann equation, developed by Wang Chang and Uhlenbeck sets up a linearized Boltzmann equation in the perturbed distribution function which is expanded in moments. Their treatment of the linearized collision integral for Maxwellian molecules by eigen-function theory fails as the Knudsen range is approached. The failure is due to the fact that the resultant dispersion relation describing the speeds of propagation and the rates of attenuation of waves generated by a wall oscillating with frequency ω has its roots expressed as a power series in ω / ν, where ν is the collision frequency. At high ω or in the Knudsen limit, this power series expansion fails.

Following the method used by Gross and Jackson to generalize the BGK model, Sirovich puts forth a kinetic model for the linearized collision integral in terms of moments, instead of solving the full Boltzmann equation. For three moments, the Krook equation results and for 5, 8 and 11 moments, higher-order approximations result from the extended kinetic theory models. The roots of the dispersion relation resulting from the set of linear, coupled equations are studied. Maxwellian and rigid sphere molecules, the limits of soft and hard interactions in a gas, have been treated although the method is general enough to allow for arbitrary models involving any number of moments.

For the case of forced sound waves, agreement with the experimental results of Greenspan is very good, better than the 483-moment and 105-moment results of Pekeris using the method of Wang Chang and Uhlenbeck. Favourable comparison with the theories of Grad, Burnett and Navier-Stokes is made.

There was some disagreement in the discussion as to whether the continuum changed for the boundary value problem or not. Sirovich maintained it was dependent upon model and number of moments. Weitzner maintained the spectrum did not change and that one had to consider other than the sound modes to show this.

5.3 Forced Sound Propagation in Gases of Arbitrary Density: Mason

The steady state sound disturbances induced in a gas of arbitrary density by anoscillating plane boundary are examined. To the right hand side of the Krook-model Boltzmann equation is added a time-dependent source term representing the effect of particle reflections from the moving surface. The exact solution of the dispersion relation of an approximate equation, obtained by using an algebraic Cauchy-type velocity distribution to represent the Maxwellian distribution function, is obtained via Fourier transforms. An approximate solution to the exact equation using the Maxwellian is obtained as well. Both solutions for a specular reflection law exhibit the proper Navier-Stokes behaviour in the continuum region and a "free-molecule" form when collisions are absent. The Maxwellian result is in acceptable quantitative agreement with experiment throughout the transition region as well.

The significance of this approach lies in the introduction of the source term to facilitate the solution of boundary value problems. The dispersion relation treatment is standard although it does extend over a range of collision frequency/oscillation frequency of $10^{-3} \leq v/w \leq 10^3$.

In the discussion, Weitzner emphasized that the results were good only for specular reflection and could change with diffuse reflection.

5.4 Propagation of an Initial Density Discontinuity: Bienkowski

The one-dimensional propagation of an initial density discontinuity is studied. Solutions for times much shorter than the collision time (i.e. "collisionless" case) and for times much longer than the collision time (i.e. the Euler limit or idealized shock-tube case) are obtained. A method for evaluating the first effect of collisions is developed for both the Krook model and the exact Maxwellian collision integral. The Krook model agrees qualitatively with the exact solution except in the region of eventual shock formation for high initial density ratios. The first-collision solution is valid up to times of the order of a mean free time on the high pressure side and the results tend toward the Navier-Stokes results. The linearized Navier-Stokes results tend to become valid for times in excess of ten mean free times. The contact surface and shock wave regions do not become separated until about 50 mean free times. After 100 mean free times, interaction between the two ceases, and at 1000 mean free times the Euler solution is approached. Approximations to the non-linear Navier-Stokes equations show roughly similar results. A note of caution is sounded as to the use of the Krook model in problems with collisions between streams of greatly differing velocities and temperatures.

5.5 Rayleigh's Problem at Low Mach Numbers According to Kinetic Theory: Cercignani and Sernagiotto

The linearized Rayleigh's problem is solved over the whole range of Knudsen numbers, for small Mach number, using the BGK model. The linearized equation can then be treated analytically using Laplace transform methodsandseparation of variables. Simple analytic expressions can be found for the shearing stress at the plate and the gas velocity at the plate. For large times, the boundary layer is the same as in the steady problem, and the slip coefficient is also the same as in the steady problem.

5.6 Numerical Experiments in Kinetic Theory: Anderson and Macomber

The authors aim to study the accuracy of certain approximation procedures in non-linear problems in kinetic theory. They have chosen two problems - Couette flow with heat transfer and the structure of a plane shock wave - where the Krook model formulation of the Boltzmann equation can be solved exactly, although numerically. The approximation procedure used on the Krook equation is to approximate the velocity dependence of the true distribution function by a form containing a finite number of space dependent parameters and selecting a finite number of moment equations to determine these parameters. In the Couette flow case, a set of ten ordinary differential equations results from the approximate procedure and a set of four singular, non-linear integral equations. Solutions of both cases have been obtained well into the Knudsen regime and for a range of temperatures and velocity ratios. The accuracy of the approximate procedure is a few percent of the exact procedure. As the Knudsen number becomes small, difficulties in convergence are experienced. The shock wave case, is solved in a similar manner.

The comparison of approximate and exact solutions of the Krook equation suggests that relatively simple procedures can yield acceptably accurate results. Thus, some justification may be obtained for extending such procedures to more complicated problems whose exact solution is not feasible.

5.7 An Analysis of Some Rarefied Gas Phenomena From the Molecular Approach: Schaetzle

The author has developed a precedure similar in principle to the Monte Carlo method. His molecular approach specifies the distribution functions at the boundaries as known conditions. A point is selected within the interior of the flow and by kinetic theory procedures integration is carried out over the distribution function around the point to determine the point properties. This procedure is carried out point by point until convergence is reached where the complete flow field is in agreement with the boundary distribution functions. The author draws a simple comparison with relaxation methods. The primary advantage claimed is that every phase of the flow field is determined from the physical motions of the individual molecules.

The method is applied to compressible flow over the leading edge of a flat plate and with slightly supersonic flow. The tangential and normal velocity jumps and the Knudsen layer are seen as well as a wave resembling a shock wave.

5.8 Near Free Molecule Behaviour of Gases with Infinite Collision Cross Section: J.J. Smolderen

Whereas most applications of the Boltzmann equation to the treatment of near free molecule flow have assumed simple molecular models with finite collision cross section, this paper presented the one dimensional problem for the case of power law type molecular interactions. Some results were derived for other infinite cross-section models such as the exponential. The interaction model is found to have a very strong effect on the nearly free molecule behaviour of the gas. Earlier results based on finite interaction distances lead to a dominant term in the assymtotic deviation from free molecule values proportional to 1/Kn log Kn (where Kn = Knudsen number). The results presented for power law molecules show leading term dependence Kn (S-1/S+1) (where S is the power law exponent) and thus a stronger deviation from the free molecule solution.

The mathematical technique used to handle the singularity occurring at the free molecule limit for infinite cross sections involves a double Fourier transformation. Numerical results are available for the one-dimensional geometry using power law molecules and the analysis is being extended to investigate the case of drag on a cylinder.

Dr. Sherman gave this work special mention in the panel discussion.

SUMMARY

Probably the most striking feature of this session is the advance made on the Boltzmann equation using the Krook collision model and fast digital computers. In Mason's problem, that of forced sound propagation, a single formulation of this technique has been used to obtain acceptable results from free-molecular flow, through the transition region, and into the continuum regime. The brute-force technique of Schaetzle has given acceptable results on one problem but it will be interesting to see whether or not it will run into convergence problems in the same area as Schaetzle says the Monte-Carlo method has.

6. SURFACE INTERACTIONS I (D. R. O'Keefe)

6.1 Classical Theory of Thermal Accommodation and Trapping: F.O. Goodman

Dr. Goodman explained that his presentation was an extension of the work on the theory of thermal accommodation reported previously in R.A.E. tech. note form*. Considerable time was spent in describing the molecular interaction model used, as well as the basic assumptions inherent in the theory. The main purpose of Dr. Goodman's presentation was to discuss the removal of two rather restrictive mathematical conditions contained in his previous analysis. He described the new methods for the removal of these and then proceeded, with the new information, to give a very excellent curve fit to the experimental data provided by Thomas at the University of Missouri. This experimental data was for the variation of the thermal accommodation coefficient for the rare gases on tungsten at different surface

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* Royal Aircraft Establishment, Farnborough, Hants, England.

temperatures. The proper choice of interaction parameters made it possible to predict this variation over the entire temperature range given. The importance of this work was reflected in the discussion period in which most speakers were complimentary of the work presented.

6.2 Theoretical Predition of Momentum and Energy Accommodation for Hypervelocity Gas Particles on an Ideal Crystal Surface: R. A. Oman, A. Bogan and C. H. Li

In this presentation, Dr. Oman described the work currently being carried out at Grumman in attempting to describe the dynamics of interaction of an energetic (1 to 10 e.v.) particle with a crystal surface. A very realistic model was proposed in which the varying angles of incidence of the incoming particles are considered, and the specific crystal lattice chosen is face-centered cubic. The problem is sufficiently complex that it must be solved using iterative methods on the IBM 7094 computer. Dr. Oman described the most basic assumption of his analysis as being the use of uncoupled Einstein oscillators in the lattice. He justified this assumption for high energy particles, explaining that a model which did take this into account would give, at most, a 10 percent variation in the result. Using statistical procedure and iterative methods, the variations of the normal and tangential momentum coefficients with incident particle energy and incident angle were described. Also presented was the variation of the thermal accommodation coefficient with the same parameters. Dr. Oman emphasized that no comparisons could be made with experiment as experimental data in the above energy range is at present not available. The discussion period was devoted almost entirely to questions requesting more detailed information on the statistical methods used, and no objections to the procedure resulted.

6.3 Atomic Scattering From a Perfect Crystal: A. J. Howsmen

This paper represented, again, an attempt to describe the interactions of a gas particle with a solid surface, however, this time employing a quantum mechanical approach. It was the belief of the speaker that the interaction problem could hopefully be solved over the entire energy range from 0.1 to 10 electron volts through the use of such a model. Howsmen believed this to be the correct approach even at energies where diffraction effects are not to be expected, since many experimentalists have measured quasi-specular lobes in their scattering patterns. This suggested to him that quantum mechanical effects were still present and that the only definite way of verifying this was to solve the problem in its entirety using quantum mechanics. His paper was a description of the procedure he was going to use.

In the discussion period which followed, the procedure of using quantum concepts for high energy particles was challenged. When asked why he preferred this complex approach, Dr. Howsmen explained that the quantum approach would give an exact analytical solution while with any classical approach one had to rely on computer work. It seemed that most people currently involved in this type of work were pleased with the fact that at last someone was going to test the classical approach.

6.4 Analog Computer Studies of Particle Surface Interactions: M. Rogers

The solution of the gas-surface interaction problem on an analog computer was very vividly demonstrated in this particular presentation. The introduction was devoted to a description of the various models of energy exchange between atoms in the gas phase and surface lattice atoms. The concepts of the non-linear model of interaction, used in the present paper, was then expanded upon. On the analog computer it was possible to study the trapping and stay times of the gas particles as they interacted with the solid. This trapped condition was demonstrated in a film which recorded the behaviour of the molecules on an incident velocity vs. distance plot as they interacted with the surface. At certain critical velocities the atoms became trapped, suffering multiple collisions with the so called well of interaction. Knowing the incident velocity and the energy with which the particle left the surface after suffering these multiple collisions, he was able to determine the energy accommodation coefficient. Comparison was made with experiment in which agreement was good for the case of light particles on a heavy lattice. The speaker explained that the interaction potential between a gas particle and a lattice atom is not known experimentally and that his non-linear model is merely an approximation to a complex situation.

6.5 The Effect of Adsorbed Monolayers on Energy Accommodation: R.E. Stickney

The paper on energy accommodation by Dr. Stickney was inserted at an appropriate time in the session, as it was most refreshing to hear a paper on the general concepts of energy accommodation after listening to the detailed attempts of energy accommodation of the previous four papers. Dr. Stickney provided the listener with a qualitative insight into the problem of energy accommodation at a surface with chemisorbed gas layers. He, in essence, emphasized the effect of surface conditions on the accommodation, an effect which was not considered in any of the dynamical models prior to this presentation. An important point made was the fact that even for gases at hypervelocity speeds (energies $\approx$ 10 ev), one had to take into account the presence of chemi-sorbed layers on the surface, as there was no guarantee that such a surface would be scrubbed clean by the impinging gas molecules. Dr. Stickney also pointed out, based on some approximate calculations, that adsorbed monolayers could give rise to a decrease in the accommodation compared to that of the clean surface.

6.6 Recent Studies of Molecular Beam Scattering From Continuously Deposited Gold Films: J. N. Smith and H. Saltsburg

In this paper, Mr. Smith presented some of his most recent work on the scattering of low energy beams performed at General Atomic. Following his earlier scattering work on nickel surfaces, he described a method for keeping his surfaces clean by continuously depositing gold on silver coated mica surfaces during the course of the measurements. The gold deposition rate was large enough so that it prevented chemisorbed layers of the background gas from forming, but yet was small enough to prevent any gas phase interactions with either the incident or scattered molecules. It was also quite easy for him to study the effect of contaminating the surface. Speakers in the discussion period were most complimentary of the technique used. Some believed that an attempt at ultra high vacuum conditions in the chamber would be a better technique for obtaining clean surfaces but Mr. Smith pointed out that the beam itself contaminated the surface and only his technique can eliminate that effect.

6.7 Scattering of Molecular Beams by Metallic Surfaces: J. J. Hinchen and W.M. Foley

'his paper represented a rather complete description of scattering u er varying beam and target temperatures, beam incident angles and surface contamination. They discussed the transition from diffuse to lobate reflection as the target surface was heated, and made measurements of the energy and momentum accommodation coefficients from the observed deviations of the scattered flux from the specular angle. They illustrated quite vividly the effect of surface contamination on the energy accommodation by measuring "α" from their phase shift experiments for an unprepared platinum surface and for one which was heated to 1000°C in a 10^{-9} torr environment. In the discussion period which followed, the use of target heating (ion - bombardment) to 1000°C was considered by some to be i adequate for proper cleaning. Dr. Hinchen defended his position by stating that the bombardment effect does give adequate cleaning even though the surface temperature is only 1000°C. Dr. Stickney from M.I.T. made the point that this is but one pa icular set of data and that others (Roach) have found decreases in accommodation with surface contamination.

6.8 On the Nature of the Surface Interaction Between Inert Gas Molecules and Engineering Surfaces: A. R. Kuhlthau and M. Bishara

This paper represented some rather preliminary work being carried out at the University of Virginia on the reflection of molecules from surfaces. The experiment consists in reflecting a beam of molecules (nitrogen) from a magnetically suspended rotating disk. Using such a device, it is possible to determine from an analysis of the scattered pattern whether or not the reflection is diffuse or multiple specular. This fact is important to the experimentalist, as the assumption of complete accommodation for a distribution which is actually multiple reflected, will give a completely false result. Dr. Kuhlthau's experiment is a unique way of distinguishing between these two models, however, as pointed out in his talk it is difficult to determine quantitatively what is happening for a reflection in which the presence of both of the above types are present. He explained that the reason for not having very much data was due to a power failure which completely demolished his rotor and associated equipment. The only statement made was the fact that from the studies performed to date, the surface interaction appears to be of the diffuse type. An unexplained result was that although the scattered distribution was found to be diffuse and Maxwellian, it apparently had a temperature 70^{o} Kelvin above that of the actual surface temperature. No plausible explanation of this was given in the discussion period to follow except that it might be a source (incident beam) problem.

7. MOLECULAR BEAMS (H. J. Davis, Jr.)

7.1 High Intensity Supersonic Molecular Beam: Roger Campargue

This paper presents experimental studies on the performance of a Kantrowitz-Grey type of molecular beam. The best performance was obtained using a capillary of length $\geq$ 2 diameters or a conical converging nozzle. Intensities of 10^{19} molecules/sec/cm^2 for hydrogen at the skimmer have been obtained.

The intensity is a function of both the stagnation pressure and the distance from the nozzle to the skimmer. A typical curve of intensity as a function of nozzle-skimmer distance shows an initial decrease followed by an increase to a maximum as the nozzle-skimmer distance is increased. The curves of intensity as a function of stagnation pressure present a maximum followed by a minimum. The mathematical surface of intensity as a function of stagnation pressure and nozzle-skimmer distance retains its general form for all gases studied and all types and sizes of nozzles employed. In all cases a peak appears. When the coordinates of stagnation pressure and nozzle-skimmer distance of this critical point are used (for systems with conical converging nozzles) the mass flow through the nozzle (which contains the term stagnation pressure) divided by the viscosity, nozzle-skimmer distance squared and the molar specific heat (at constant volume and low temperature) remains approximately constant for all 24 gases studied. All the experiments were performed under constant pumping conditions.

A study of the expansion ratio across the nozzle is currently in progress.

Dr. O. Hagena commented that it would be convenient if all workers in the field would give intensities in the units of molecules/sec per unit solid angle. This would make the intensity independent of the special piece of experimental equipment and allow easy comparisons. This suggestion was acclaimed by many members of the audience.

7.2 Studies of Low Density Supersonic Jets: J. B. Anderson, R. P. Andres, J. B. Fenn and G. Maise

Results of experimental studies of supersonic jets of the type used in Kantrowitz-Grey molecular beams were given.

Earlier work showed a remarkable adherence of Pitot measurements to the predictions of the Owen and Thornhill method of characteristics calculation except at low beam density where a "droop" from these calculated curves was found. Recent measurements with a number of different Pitot tube diameters shows that this "droop" is caused by viscous effects at the probe. These effects occur at higher Reynolds numbers than has been suggested by previous work which was done at lower Mach numbers.

From velocity distribution investigations with time of flight measurements, it was possible to ascertain under what conditions in the jet the expansion ceased to be describable in continuum terms. A strong correlation between maximum Mach number achievable and the Knudsen number at the throat appears. With argon at room temperature observed distributions give corresponding Mach numbers in the jet as high as 23.

A probe to give an accurate measurement of adiabatic stagnation recovery temperature was developed. One particular case of 20% argon in 80% helium expanded from a source temperature of 309°K showed a recovery temperature of 430°K.

Professor E. L. Knuth, commented on the use of Pitot probes in a free jet of Nitrogen where the rotational degrees of freedom have become frozen. The correction factor for the Pitot tube may differ by as much as a factor of 2 if freezing is taken into account but a plot of Pitot tube pressure factor versus Reynolds number is not affected much by neglecting the freezing.

Professor K. Bier, asked whether the fact that the observed recovery temperature of the argon-helium mixture was higher than the theoretical value for free molecular flow was an indication of separation of the two gases in the free expanding jet?

Professor J. B. Anderson replied that this mechanism would explain what was observed, but the authors are inclined to think the separation occurred at the probe instead of in the free jet.

7.3 Optimum Conditions for Generating Molecular Beams by Nozzles: K. Bier and O. Hagena

A large increase in the pressure ratio across the nozzle of a Kantrowitz-Grey molecular beam was achieved by allowing the gas to expand through the nozzle in intermittent pulses rather than continuously. A quick acting valve upstream of the nozzle settling chamber gave pulse lengths of 2 - 5 x 10^{-3} sec. with the gases N_2, Ar and He.

The time slope of the total particle density of the beam was obtained with an ionization detector. Velocity distribution of the beam pulses was obtained using a time-of-flight set up supplemented by a synchronized electrical circuit with adjustable time delay so that the velocity distribution could be measured at any arbitrary time within the beam pulse.

With CO_2, N_2, Ar, and He as beam gases, Mach numbers of 8, 13, 19, 25 with particle flow densities of approximately 1.2 x 10^{18}, 2.5 x 10^{18}, 1.8 x 10^{18}, and 3.6 x 10^{19} particles/rad^2sec. respectively were achieved under optimum conditions.

The relation between inlet pressure and optimum nozzle to skimmer distance, influence of nozzle diameter and skimmer shape on Mach number and intensity, and the possibilities of obtaining still higher Mach numbers and intensities were discussed.

7.4 Omegatron Studies of a Skimmed Beam System: D.R. O'Keefe and J.B. French

This paper presented experimental studies of seeded Kantrowitz-Grey type molecular beams. The experiments were performed using an omegatron partial pressure analyser downstream of the skimmer. The seeded beam had a mixture in the settling chamber of 1% argon (by number of molecules) in 99% helium.

Measurements of flux into the collimator of the omegatron indicate a flux somewhat less than predicted by isentropic theory. At large nozzle-skimmer distances the flow into the skimmer contained 4% argon.

Measurements were taken of the radial distribution of intensities of the two gases in the mixture and of the argon alone with the helium shut off. The skimmer was 24 source diameters downstream of the source nozzle. The curves obtained showed that the argon is very much more collimated when it is mixed with helium.

With certain assumptions about the nature of the free jet expansion it was shown that for large nozzle-skimmer distances a plot of the flux (times geometric factors) on a log scale as a function of the square of the ratio of radial position to distance downstream of the skimmer of the omegatron orifice should yield a straight line. The slope of the straight line is minus the square of the speed ratio. Analyzing the data on this basis yielded M = 28.8 for the helium in the mixture compared to the isentropic value of 27.3. Assuming the argon in the mixture shares the same directed velocity and temperature as the helium yielded M = 86.7 for the argon while M = 67.5 was obtained from the data. Possible explanations for the difference is slip of the heavy molecules relative to the light ones in the latter stages of the expansion, or the diverging nature of the flow not considered in the theory.

7.5 Distribution Function Measurements in Rarefied Gas Flow Through an Orifice: J. E. Scott, Jr., H.S. Morton, Jr. J.A. Phipps, and J.F. Moonan

In order to demonstrate the validity of measuring the distribution of molecular velocities in a Kantrowitz-Grey type molecular beam with a mechanical velocity selector the selector was used to measure the distribution function of beams formed by molecular effusion through a plane orifice.

Measurements were made for argon beams over the range of source Knudsen numbers from 10 to 0.5 and for Xenon beams with source Knudsen numbers from 10 to 0.1. For Knudsen numbers greater than about 5 it was found that within experimental error, the beam distribution was independent of source density and corresponds to the classical Maxwellian distribution. With Knudsen numbers as large as 2 the effects of collisions in the vicinity of the orifice are recognizable from the increase in the most probable speed and a decrease in the width of the distribution.

The experimentally measured beam distributions were compared with distributions calculated by solving the Boltzmann equation along the beam axis in an approximate manner by using the relaxation time model for the collision term proposed by Krook. Agreement between experimental results and the approximate theory was considered satisfactory for a source Knudsen number of order unity.

7.6 Background and Sampling Effects in Free Jet Studies by Molecular Beam Measurements: J.B. Anderson and J. B. Fenn

This paper presented the results of experimental studies designed to determine the causes of observed departures from ideal behaviour of Kantrowitz-Grey types of molecular beams. The studies consisted of beam intensities and velocity distributions under a wide variety of operating conditions.

Part of the observed loss in ideal intensity was shown to be due to background scattering of the free jet in the nozzle exhaust chamber and the conditions for this loss were characterized in terms of jet density.

Measurements of the velocity distributed in the beam with a time of flight method allowed the following conclusions to be made about the jet-skimmer interaction. For values of Knudsen/Mach number at the skimmer greater than unity both the centerline velocity distribution and intensity of the final beam are unaffected by the presence of the skimmer. For Knudsen/Mach number from 0.2 to 1 the centerline velocity distribution is only slightly altered by the intensity may be as low as 20% of theory. With values of Knudsen/Mach numbers less than 0.2 the velocity distribution is greatly broadened and intensity is only a small fraction of the theoretical value. The studies show that collisions of beam molecules with molecules reflected from the internal walls of the skimmer may be just as important as the effects of the front or external walls.

Preliminary results were given for a liquid N_2 cooled skimmer with CO_2 beams to indicate the nature of the jet-skimmer interaction and to assess the importance of self-collisions in the beam downstream of the skimmer.

7.7 Velocity and Composition of Supersonic Molecular Beams From Measurements of Total Collision Cross-Sections: R.G. Albright, J. Peeters, M. Bourguignon, R.L. LeRoy, and J.M. Deckers

The intensity of a Kantrowitz-Grey type of molecular beam was measured after it had traversed a box in which the pressure could be changed. When the logarithm of beam intensity was plotted as a function of pressure in the scattering box a straight line was obtained whose slope was proportional to the effective total cross-section, Q_{eff}, for the interaction between the beam and the scattering gas in the box.

Nitrogen-hydrogen and nitrogen-helium mixtures were expanded through the nozzle while only nitrogen was admitted to the scattering box. The value of Q_{eff} was measured as a function of the distance from nozzle orifice to skimmer and the proportion of light gas in the initial mixture.

Assuming the stream velocities for both molecular species was the same during the expansion an average velocity, V, of the beam molecules was calculated and correlated with the values of Q_{eff} measured experimentally. The reduction of the data gave a straight line plot for the log of the effective total cross-section corrected for the thermal distribution of velocities among the scattering gas molecules, Q, as a function of the log of V. The slope of -2/3 obtained agreed with that predicted by classical scattering theory. With the ligher gas increased to more than 85% of the initial mixture the values deviated from the classical straight line and this was attributed to the presence of light gas in the final beam.

For a final beam of pure nitrogen and with the established dependence of Q_{eff} upon V the measurement of Q_{eff} made it possible to determine the stream velocity. This technique was used to investigate the dependence of beam velocities on the nozzle-skimmer distance. It was found that with an initial mixture of more than 40% of the ligher gas the stream velocity did not vary significantly as a function of nozzle-skimmer distances greater than about two nozzle diameters.

8. INTERNAL FLOW AND RAREFIED PLASMA (P. Hughes and A. Sonin)

In the first paper on internal flow, Shidlovsky (the paper was actually given by an interpreter) discussed the shape optimization of an axi-symmetrical body at zero angle of attack to a free molecule flow to minimize drag. The variational problem involved was formulated in terms of three parameters associated with the flow Mach number, the body/flow temperature ratio, and the accommodation coefficient. A consideration of the first integral of the resulting Euler-Lagrange equation showed that if the nose is pointed the body is in fact a cone, for minimum drag. If the nose is not pointed, a nose drag term is added to the integral (avoiding infinite slope problems) for the drag due to the remainder of the body and the analysis proceeds as before.

The second paper (co-authored by Townsend, Patterson, and Sinclair) was concerned with free molecule flow through conical tubes. Assuming perfect energy accommodation at the wall and an arbitrary wall temperature distribution, the authors developed integral equations for the mass, energy, and axial momentum flows down a tube at rest in a Maxwellian gas. The mass flow calculation was then extended to the case where the conical tube is at zero angle of attack to a Maxwellian flow of arbitrary speed ratio. A discussion of sample curves based on numerical computation concluded the presentation.

The next paper by Wu set up integral equations for the number flux incident on a surface bounding a free molecule or near free molecule gas. The near free molecule case is solved by means of assuming the solution to be the free molecule solution plus a power series in the small parameters ν , the collision frequency. The procedure used for solving these equations was an application of matrix equations via finite differences. In the case of free molecule flow, an alternative approach was indicated which utilized a Markov chains process to formulate a probability model.

The final paper on internal flow (co-authored by Hughes and deLeeuw) reported on analysis of a free molecule pressure probe in which the "collecting tube" is cylindrical. The ratio of the static pressure in the gauge volume to that of the free stream (assumed drifting Maxwellian) was calculated in terms of tube length, probe angle of attack and flow speed ratio. The approach taken allowed the general case to be reduced to a double integration which as to be performed numerically. These computed results were shown graphically and corroborating experimental evidence was presented. One important conclusion was that a finite tube does not have a pressure ratio of unity when at right angles to the flow.

The section devoted to rarefield plasmas started with M. Perlmutter's presentation of a Monte Carlo solution for the flow of a highly rarefied charged gas through a finite channel with transverse magnetic field. Flow rates and density distributions were calculated for various values of field strength, with a Maxwellian velocity distribution assumed at the inlet.

The next two papers were directed to the theory of electrostatic probes. J. Laframboise presented a computer solution for the complete characteristics of both spherical and cylindrical probes in a rarefied plasma at rest. In his solution both the electrons and ions were assumed to have Maxwellian velocity distributions far from the probe, although with different temperatures, and space charge effects were completely accounted for. The curves presented represent the most rigorous solution of this problem available to date, and should be of considerable interest to experimental workers using the Langmuir probe technique. E. Wasserstrom considered the problem of the spherical probe from a different, kinetic theory point of view. On the assumption that velocity space can be divided into two regions with different distribution functions, he obtained solutions which are appropriate to all mean free paths, at least for Maxwellian molecules. The weak point in the theory, Wasserstrom emphasized in reply to some questions, lies in the rather arbitrarily made division of the velocity space into two regions.

S.H. Lam's paper dealt with the disturbance caused about a solid body in a flowing rarefied plasma. His analysis, which was restricted to cases in which the thermal speed of the ions is negligible compared to the flow speed, is well suited to the study of satellite-ionosphere interactions and also to the interpretation of Langmuir probe data in hypersonic flows. With the additional assumptions of large mean free path, small Debye length and highly, negatively charged body, Lam had obtained solutions for the supersonic flows over a cone and a wedge, and the subsonic flow over a sphere. In answer to a query regarding the meaning of a subsonic solution for a case in which the mean thermal speed has been assumed to be much less than the flow speed, Lam stated that in that limit one can simply recover the solution of Allen, Boyd and Reynolds.

In the last paper, which was the only one describing experimental work in this field, W.A. Clayden presented the results of a laboratory experiment in which a pulse of neutral gas was released into a partially ionized gas in the presence of a magnetic field, to simulate the redistribution of charged particles in the ionosphere caused by a disturbance.

9. SURFACE INTERACTIONS II AND MISCELLANEOUS (E. J. Moskal)

The first paper by G. T. Skinner and B. H. Fetz of Cornell Aeronautical Laboratory, presented preliminary results on momentum accommodation using a high energy molecular beam. A shock tube was used to feed a nozzle from which the beam was extracted by the use of two skimmers and two collimators. The 1.2 e.v. nearly monoenergetic beam had a 1% directional spread at the last collimator. The working beam flux was on the order of 2×10^{18} molecules/cm^2sec. Effects of copper dust from the diaphragm were minimized. Final chamber pressures gave a mean free path of a few millimetres. Preliminary measurements gave values for the accommodation coefficient in the range 1.2 to 1.5. The high readings cannot be accounted for by experimental error. It was emphasized that the above results show the method is feasible and proper readings could be obtained on further improvement of the apparatus. The scatter in the results was thought to be caused by the fact that the process involves an unsteady expansion. It was also pointed out that the energies of the beam were quite reproducible from run to run.

A very thorough study of the condensation coefficients, time required for diffusion, and the binding energies of indium atoms on several surfaces, was given by G. H. Miller of Sandia Corporation. The basic measuring and detection process used was the surface ionization method. This process depends on having a constant beam intensity, and upon ionizing a constant fraction of the desorbed or scattered atoms coming from the target or detector plate. The desired quantities can then be extracted from theory, assuming that the matehmatical formulae completely describe the physical situation. It was also noted that under certain unfavourable conditions, small changes in the work function or in the temperature of the material would give large changes in the ionization efficiency. Preliminary measurements were given and discussed, and the values of desorption energies derived by independent methods were found to agree within experimental error. This detection system seems to be very promising, and reduction of the temperature spread of the target, knowledge of the surface conditions, and reduction of background pressures from 10^{-8} to 10^{-10} mm Hg will probably yield valuable results. Using an Indium beam, however, this system is limited to approximately forty elements for the target.

An electron beam technique was discussed by D. J. Marsden of UTIAS as a method to obtain energy accommodation coefficients for translational and rotational degrees of freedom of diatomic and polyatomic gases on solid surfaces, in particular nitrogen on a silver surface. The basic principle used in the measurements is that for less than ten microns Hg pressures, the intensity of light emitted by a gas, when it is excited by an electron beam, is proportional to the density of the gas. The results given in the symposium were qualitative, because the technique used was basically a new approach to the measurement of accommodation coefficients, and as such, is still in the process of being perfected. However, preliminary results show that it is possible to obtain not only translational accommodation coefficients from the total light intensity, but also rotational accommodation coefficients from analysis of rotational fine line structure in the emitted light. The latter is a result which has previously been unattainable, and considerable interest was shown in this feature. The above electron beam technique can be used to number densities corresponding to 10^{-5} mm Hg. Also, gases to be investigated would have to give reasonably strong spectral lines which could then be detected by the available instrumentation.

A R.F. ion source was used by F.M. Devienne to generate an argon beam having energies in the 500 to 3000 e.v. range. A standard deviation of less than 5% characterized some of the presented data. Effects of surface contamination on the values of the accommodation coefficient could not be estimated as background pressures were on the order of 10^{-6} mm Hg. In the question period, it was brought out that there are many sputtered particles and these are currently being investigated. The effect of sputtering was not taken into account in the calculation of the energy accommodation coefficients.

J. Souquet presented an investigation of surfaces bombarded by a beam of argon atoms having an energy of 60 to 3000 e.v., and a flux of approximately 5×10^{12} molecules/cm^2sec, under various angles of incidence. A secondary aluminum target could be placed such that it could detect particles coming off at any angle from the primary target. The results presented were of a qualitative nature. The ratio of the maximum current due to the particles coming off at a specular angle, to that coming off at a diffuse angle (normal to the surface) was investigated with respect to energy of incoming beam, variation of angle of incidence of beam with primary surface, variation with different types of surfaces, and variation with the surface state. In addition, the detector was put in planes other than that formed by the incoming beam and the normal to the primary surface. A third lobe in the current plots was found at an angle of 17° to the normal. This lobe seemed to be universal for his plots. In the question period, it was suggested that the "diffuse" lobe was formed of sputtered particles which were, in general, ions. The lobe at the spectral angle was assumed to be due to elastically scattered particles as they had approximately the same energy as the incoming atoms and were neutrals. The lobe at 17° was composed of neutrals. No explanation for this lobe was offered.

At the present time, there is little experimental data on flow in the transition and slip regimes. In the final paper of the session, by T. Rogers and J.C. Williams III, an experimental investigation of the flow of nitrogen in a rectangular duct at low Reynolds number and an initial velocity of M = 9, was given. For a constant area or convergent channel, a normal shock wave was formed ahead of the channel. In a slightly divergent channel, a shock-like, bell-shaped, transition boundary extended back into the duct, and each plate seems to start to act independently of the other. Velocity, Mach number, and total pressure profiles were presented, and slip velocities and skin friction coefficients obtained.

In conclusion it can be stated that methods for measurement of accommodation coefficients have not advanced far enough so that the various experimenters are in agreement. However, this conference has shown that the problems involved in the production of molecular beams, along with measurement techniques, are being solved, and meaningful data should soon be available.

10. SHOCK WAVE STRUCTURE (D. E. Rothe and P.V. Marrone)

Nine papers were given at this session, with three of the authors presenting experimental results on shock wave profiles and shock thickness measurements. It may be noted that all three of the experimental papers presented data obtained with similar facilities, i.e. the shock tube with an electron beam being used to obtain the shock density profiles. The most discussed source of experimental error was the effect of shock wave curvature which affects the interpretation of gas density measurements obtained from the electron beam absorption or scattering. The curvature may also cast some doubt on the one-dimensionality of the flow through the shock wave.

The six theoretical papers presented solutions for new physical models used to describe the molecular kinetics, as well as refinements of the mathematical techniques used to solve the equations. It appears that shock structure theory has progressed to a point where good experimental data is now needed to justify one method of solution as preferred to another. Fortunately, this session provided an insight in both the theoretical and experimental areas. Based on the measurement of argon shock thickness up to Mach 20, for example, the Mott-Smith bimodal solution or the BGK computation presented by Chahine predict the experimental values very closely for a wide range of Mach numbers. The Navier-Stokes predictions, however, indicate shock wave thicknesses much smaller than those actually measured.

There was a stimulating discussion following each presentation and it is felt that the trend will be towards a greater effort of research in this area during the next few years. The use of steady flow, low density facilities should yield additional experimental data complementing the results obtained in shock tubes.

10.1 Experimental Papers

Each of the experimental papers presented data obtained from a shock tube, with an electron beam passing across the tube. The scattered beam electrons in the shock front were detected by Camac, while Schultz-Grunow and Russell measured the attenuation of the primary beam.

Since Camac performed his experiments in a large diameter tube (i.e. 24" dia.), and investigated only the center of the shock wave, the effect of shock curvature on the data was minimized. The argon shock thickness measurements presented by Camac were extended up to M = 20, and best agreement with theory seemed to be with the Mott-Smith bimodal theory using $\nu = 0.75$ (i.e. $k \propto T^{\nu}$) or with the BGK computation with $\nu = 0.816$. Additional measurements on shock waves in CO_2 were presented, indicating that translation and rotation are closely coupled in the shock front, with the excitation of vibrational modes lagging at the lower Mach numbers, but essentially completed in the shock front above M = 14.

Shultz-Grunow presented results for argon shock thickness, but since a small shock tube was used (i.e. approximately 2" x 2" cross section), the familiar low density shock tube effect introduced error into the measurements above about M = 5. Up to this Mach number, his data confirms the Mott-Smith solution. It may be noted that the effects of shock curvature were investigated both theoretically and experimentally in this paper.

Using a larger shock tube (i.e. 17" dia.) Russell measured argon shock thicknesses up to M = 8. His data is in close agreement with the data of the other investigators, also agreeing extremely well with the predictions of the Mott-Smith model and the BGK calculation presented by Chahine.

10.2 Theoretical Papers

The paper presented by Chahine (the title of which was changed to "Exact Numerical Solution of the Complete BGK Equation for Strong Shock Waves") served to illustrate the convergence of the iterative solution of the complete BGK equation discussed in earlier work by the same author. Shock wave profiles and thicknesses for argon up to M = 10 were computed, and agreed exceptionally well with experimental data of Camac, Russell, Etc. It is interesting to note that Chahine indicated that an accuracy of 2% or better would be needed in experiments to determine the asymmetry of the shock profile predicted by the Krook model. (The experimental results presented at this session showed no indication of a nonsymmetrical density profile through the shock front).

Oguchi presented a physical insight into the shock structure problem by utilizing the simplifying assumption of molecular beam-like flow. This assumption greatly simplifies the equations and allows extensive application over a wide range of Mach numbers. Shock profiles were calculated for a monatomic gas at M = 5, 10, and showed remarkably good agreement with the exact solutions of Liepmann, Narasimha and Chahine. Thus, as pointed out by the author, the satisfactory agreement with the exact solution justifies the applicability of this greatly simplified analysis within the overall validity of the BGK model.

A variation of the Mott-Smith bimodal distribution function was used by Holway who, in calculating shock structure, assumed that the downstream distribution function was ellipsoidal rather than spherically symmetrical in velocity space. When compared to the Mott-Smith calculations Holway's work predicts a slightly narrower shock at low Mach numbers and a somewhat wider shock at higher Mach numbers ($M > 3$). It was indicated by the author that for an infinite upstream Mach number the calculated temperature profile in argon shows a maximum "temperature" within the shock wave lying a few percent above the downstream equilibrium value. The accuracy of available experimental data is not sufficient at this time to determine whether Holway's ellipsoidal distribution function results in a significant improvement over the Mott-Smith model.

Using the Mott-Smith method together with a generalized Rankine-Hugoniot relation Fujimoto calculated number density profiles for the components of a binary gas mixture passing through a normal shock. He reported specific calculations for a 50-50% Xenon isotope mixture and for a 50-50% Neon-argon mixture. This result predicts a separation of the species in the shock transition which is most pronounced for a Mach number of about 4. The heavy gas always shows a concentration peak on the downstream side of the shock wave. In this respect Fujimoto's calculations are in qualitative agreement with Sherman's previous calculations based on the Navier-Stokes equations. Experimental verification of the phenomenon has not yet been reported in detail.

APPENDIX A

Technical Program

Monday, July 13, 6:00 - 7:30 p.m. - Ballroom, Royal York Hotel.
Official reception of Symposium delegates and their wives by the University of Toronto.

Tuesday, July 14, 9:00 - 9:15 a.m. - Ballroom
Official welcome on behalf of the University of Toronto by Dr. R.R. McLaughlin, Dean of the Faculty of Applied Science and Engineering.

Tuesday, July 14, 9:15 - 12:30 a.m. - Ballroom
Transition Flow - Experimental I
Chairman: Dr. H.H. Kurzweg, Director of Research, National Aeronautics and Space Administration

An Experimental Study of Surface and Flow Field Effects in Hypersonic, Low Density Flow Over a Flat Plate	J. Wallace and A. Burke
Recent Extensions of Nearly Free Molecular Flow Experiment and Theory	G.J. Maslach, D.R. Willis, S. Tang and D. Ko
Drag Measurements in Slip and Transition Flow	E.A. Brun, H. Coudeville and P. Trepaud
Coffee	
Experimental Studies of Surface Slip and Shock Wave Transport Effects in Hypersonic Wedge-Flows	R.J. Vidal and J.A. Bartz
Some Exploratory Experimental Studies of Hypersonic Low Density Effects on Flat Plates and Cones	I.E. Vas, J. McDougall, G. Koppenwallner and S.M. Bogdonoff
Experimental Study of Low Pressure Hypersonic Flow by Using an Electron-Beam Densitometer	I. Wada
Research at the NPL on the Influence at Supersonic Speeds and Low Reynolds Numbers of Thick Laminar Boundary Layers	E.W.E. Rogers and C.J. Berry

Tuesday, July 14, 2:00 - 5:05 p.m. - Ballroom

Transition Flow - Theoretical I
Chairman: Academician L. I. Sedov, Academy of Sciences, U.S.S.R.
Professor of Hydromechanics, Moscow State University

A Uniformly Valid Asymptotic Theory of Linearized Rarefied Gas Flows Under Nearly Free Molecular Conditions	Y. Pao
Drag on a Cylinder in Nearly-Free Molecular Flow	Marian H. Rose
Near Free Molecular Behaviour of Gases with Infinite Collision Cross Section	J. J. Smolderen
Coffee	
Improved "First-Collision" Model Theory	M. Lunc
Steady Expansions at High Speed Ratio Using the B-G-K Kinetic Model	J. W. Brook and R. A. Oman
Bimodal Two-Stream Distribution and Compressible Couette Flow	J. W. Beck
A Discrete Ordinate Technique for the Linearized Boltzmann Equation with Application to Couette Flow	B. Hamal and M. Wachman

Tuesday, July 14, 7:30 p.m. New Brunswick Room, Royal York Hotel.
Dinner Meeting of the Advisory Committee.

Tuesday, July 14, 7:00 - 10:00 p.m.
International Aerospace Exhibition at the Royal Ontario Museum, University of Toronto

Wednesday, July 15, 9:00 - 12:30 a.m. - Ballroom

Experimental Techniques and Apparatus
Chairman: Dr. W. J. Price, Executive Director,
Air Force Office of Scientific Research
U.S.A.F.

Free Jet Testing in Low Density Wind Tunnels	H. Ashkenas and F.S. Sherman
The Direct Measurement of Velocity Distribution Functions	E.P. Muntz
Impact and Static Pressure Measurements in High Speed Flows with Transitional Knudsen Numbers	K.W. Rogers, K.J. Touryan, J.B. Wainwright and H.T. Yang
Influence of the Orifice on Measured Pressures in Rarefied Flow	J. L. Potter, M. Kinslow and D.E. Boylan
Coffee	
A Discharge Probe for Transient Density Measurements in Rarefied Gas Flows	D.S. Rigney, A.J. Schwalb and M.E. Levy
Condensation of Rarefied Sypersonic Flow Incident on a Cold Flat Plate	E. Mayer, R. Tracy, J.A. Collins and M.J. Triplett
Low Density Boundary Layer Control by Liquid Hydrogen Cryopumping	W.N. MacDermott, B.H. Shirley and R.E. Dix
A Radial-Flow Turbomolecular Vacuum Pump	S.F. Iacobellis and E.L. Knuth

Wednesday, July 15, 2:00 - 3:50 p.m. - Ballroom

Transition Flow - Theoretical II
Experimental II
Chairman: Dr. W. Petrie,
Deputy Chief Scientist,
Defence Research Board (Canada)

Kinetic Theory of the Leading Edge	S. Ziering, L. Chi and R. Fante
The Incipient Continuum Flow Regime Near the Leading Edge of a Flat Plate in Hypersonic Flow	J.M. Ii and R.E. Street
Investigations of the Flow Field Near the Leading Edge of a Heated Flat Plate in a Mach 0.5 Air Flow	S.A. Gordon
The Aerodynamic Drag Torque on a Rotating Sphere in the Transition Regime	R.G. Lord and P.J. Harbour
Some Experiments on the Flow of a Rarefied Gas Through a Circular Orifice	A.K. Sreekanth

Wednesday, July 15, 4:15 p.m.

Scenic trip to Niagara Falls and dinner at the Seagram Tower.

Thursday, July 16, 9:00 - 12:30 a.m.

Session A - Ballroom

Surface Interactions I
Chairman: Professor F.C. Hurlbut,
Division of Aeronautical Sciences,
College of Engineering,
University of California

On the Theory of Accommodation Coefficients V. Classical Theory of Thermal Accommodation and Trapping	F.O. Goodman
Theoretical Prediction of Momentum and Energy Accommodation for Hypervelocity Gas Particles on an Ideal Crystal Surface	R.A. Oman, A. Bogan and C.H. Li
Atomic Scattering from a Perfect Crystal	A.J. Howsmon
Coffee	
Analog Computer Studies of Particle Surface Interactions	M. Rogers
The Effect of Adsorbed Monolayers on Energy Accommodation	R.E. Stickney
Recent Studies of Molecular Beam Scattering from Continuously Deposited Gold Films	J.N. Smith, Jr. and H. Saltsburg
Scattering of Molecular Beams by Metallic Surfaces	J.J. Hinchen and W.M. Foley
On the Nature of the Surface Interaction Between Inert Gas Molecules and Engineering Surfaces	A.K. Kuhlthau and M. Bishara

Thursday, July 16, 9:00 - 12:30 a.m.

Session B - Ontario Room

Kinetic Theory
Chairman: Professor R. E. Street,
Department of Aeronautics and Astronautics,
University of Washington

A Study of a Two-Dimensional Gas by the Discrete Velocity Method	J. E. Broadwell
Steady-State Oscillations in a Gas	H. Weitzner
Sound Propagation in Rigid Sphere and Maxwell Force Law Gases	L. Sirovich and J. K. Thurber
Coffee	
Forced Sound Propagation in Gases of Arbitrary Density	R. J. Mason, Jr.
Propagation of an Initial Density Discontinuity	G. Bienkowski
Rayleigh's Problem at Low Mach Numbers According to Kinetic Theory	C. Cercignani and F. Sernagiotto
Numerical Experiments in Kinetic Theory	D. G. Anderson and H. K. Macomber
An Analysis of Some Rarefied Gas Phenomena From the Molecular Approach	W. J. Schaetzle

Thursday, July 16, 2:00 - 5:00 p.m.

Session A - Ballroom

Molecular Beams
Chairman: Professor F.S. Sherman,
Division of Aeronautical Sciences,
College of Engineering,
University of California

Background and Sampling Effects in Free Jet Studies by Molecular Beam Measurements	J.B. Anderson and J.B. Fenn
Optinum Conditions for Generating Molecular Beams by Nozzles	K. Bier and O. Hagena
High Intensity Supersonic Molecular Beam Apparatus	R. Campargue
Omegatron Studies of a Skimmed Beam System	D.R. O'Keefe and J.B. French
Coffee	
Distribution Function Measurements in Rarefied Gas Flow Through an Orifice	J.E. Scott, Jr., H.S. Morton, Jr., J.A. Phipps and J.F. Moonan
Studies of Low Density Supersonic Jets	J.B. Anderson, R.P. Andres, J.B. Fenn and G. Maise
Velocity and Composition of Supersonic Molecular Beams from Measurements of Total Collision Cross-Sections	R.C. Albright, J. Peeters, M. Bourguignon, R.L. LeRoy and J.M. Deckers

Thursday, July 16, 2:00 - 5:00 p.m.

Session B - Ontario Room

Internal Flow and Rarefied Plasma
Chairman: Professor H. Oguchi,
Aeronautical Research Institute,
University of Tokyo

Some Problems of Nose Drag Minimization for Bodies in Free-Molecule Flow	**V.P. Shidlovsky**
Free-Molecule Flow Through Conical Tubes	**S.J. Townsend, G.N. Patterson and S.R.M. Sinclair**
On the Internal Flow of Rarefied Gases	**Y. Wu**
The Free Molecule Impact Probe at Angle of Attack	**P.C. Hughes and J.H. de Leeuw**
Monte Carlo Solution of Highly Rarefied Ionized Gas Flowing Through a Channel With a Transverse Magnetic Field	**M. Perlmutter**
Coffee	
Theory of Electrostatic Probes in Collisionless Plasmas at Rest	J. Laframboise
A Kinetic Theory Approach to Electrostatic Probes	E. Wasserstrom
On the Interactions of a Solid Body with a Flowing Collisionless Plasma	S.H. Lam and M. Greenblatt
Laboratory Simulation of the Redistribution of Charged Particles Caused by a Neutral Gas Cloud Expanding Into the Ionosphere	W.A. Clayden and C.V. Hurdle

Thursday, July 16, 7:00 - 10:00 p.m.

Open House at the Institute for Aerospace Studies,
University of Toronto

Friday, July 17, 9:00 - 12:30 a.m.

Session A -- Ballroom

Surface Interactions II and Miscellaneous Papers
Chairman: Professor J.B. Fenn
Department of Aerospace and Mechanical Sciences,
School of Engineering and Applied Science,
Princeton University

Measurement of Normal Momentum Accommodation Coefficients with a 1.2 e.v. Pulsed Beam	G. T. Skinner and B.H. Fetz
Interactions of Atoms and Surfaces	G.H. Miller
The Measurement of Energy Transfer in Gas-Solid Surface Interactions Using Electron Excited Emission of Light	D.J. Marsden
Variation of the Accommodation Coefficients of High Speed Molecules of Argon in Terms of Different Parameters	F.M. Devienne
Coffee	
Study of the Scattering of High Energy Molecules by Various Surfaces	F.M. Devienne, J. Souquet and J.C. Roustan
Experimental Investigation of Low Density Axial Flow Through Short Tapered Ducts	T. Rogers and J.C. Williams

Friday, July 17, 9:00 - 12:30 a.m.

Session B - Ontario Room

Shock Structure
Chairman: Professor J. Laufer, Chairman, Graduate Department of Aerospace Studies, University of Southern California

Exact Numerical Solution of the Bhatnagar-Gross-Krook Distribution Function for Strong Shock Waves	M. T. Chahine and R. Narasimha
Shock Wave Structure in Highly Rarefied Flows	D. Battat
Molecular Beam Approximation for a Shock-Structure Problem	H. Oguchi
Kinetic Theory of Shock Structure Using an Ellipsoidal Distribution Function	L. H. Holway, Jr.
Shock Wave Structures in a Rigid Sphere Gas	G. A. Bird
Coffee	
Shock Wave Structure in Binary Gas Mixtures with No Chemical Reaction	T. Fujimoto
Experimental Measurements of Shock Structure	M. Camac
Density Distribution in Shock Waves Travelling in Rarefied Gases	F. Schultz-Grunow and A. Frohn
Shock-Thickness Measurements in the GALCIT 17-Inch Shock Tube	D. A. Russell

Friday, July 17, 2:00 - 3:30 p.m. - Ballroom

Discussion and Assessment of the Highlights of the Fourth Symposium

Panel Members

Professor D. W. Holder, Chairman,
Department of Engineering Science,
University of Oxford,
(Panel Chairman)

Professor E. A. Brun,
Directeur du Laboratoire de
Mecanique des Fluides,
Faculte des Sciences,
Universite de Paris

Professor H. Grad,
Courant Institute of Mathematics,
New York University

Dr. C. Kaplan,
Mechanics Department,
Johns Hopkins University

Professor F. S. Sherman,
Division of Aeronautical Sciences,
College of Engineering,
University of California

Friday, July 17, 3:45 p.m.

Trip to the Stratford Festival Theatre to see the Shakespearean play "Richard II".

APPENDIX B

List of Delegates

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APPENDIX C

International Aerospace Exhibition cosponsored by the Institute for Aerospace Studies and the Royal Ontario Museum both of the University of Toronto

The exhibition was planned to ake place in conjunction with the Fourth International Symposium in Rarefied Gas Dynamics, 14 to 17 July, 1964, and cosponsored by the University of Toronto, Institute for Aerospace Studies (UTIAS). The staff at UTIAS designed 12 special displays for this purpose which illustrated the basic nature of the research being conducted at UTIAS over a very wide range of modern fluid mechanics, satellite dynamics, structures and materials. The above were supplemented by 40 items from the National Aeronautics and Space Administration (NASA) (mainly descriptive panels), which included a model of the Mercury Spacecraft and a mannequin in full space garb. A model of Alouette I was supplied by Defence Research Telecommunications Establishment (DRTE) and a number of descriptive panels. Canadian Bristol Aerojet contributed a model of Black Brant and a number of panels. National Research Council supplied a number of exhibits on modern fluid mechanics and turbines and DeHavilland helped to produce the gravity stabilized satellite exhibit.

The exhibition has helped to give greater substance and understanding of the aerospace sciences to the public, in particular teachers and school children who may someday enter this field of endeavour as a result of this first contact. It was estimated that about 250,000 people viewed the exhibition. If the uncounted conducted tours are added to those officially counted at the Royal Ontario Museum (ROM), then this figure will be exceeded. We can say that it was an "unqualified success".

Special lectures were given by Dr. J.B. French and Dr. I.I. Glass on the exhibition and aerospace research in Canada to groups of mathematics and science teachers from secondary schools in Ontario.

Thanks are due to the UTIAS staff and students, NASA, DRTE, NRC, DeHavilland and Bristol Aerojet for their exhibits and ROM for arranging them.